JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Article

pubs.acs.org/JAFC

Hull Split and Damaged Almond Volatiles Attract Male and Female Navel Orangeworm Moths

John J. Beck,*[,†] Bradley S. Higbee,[‡] Douglas M. Light,[†] Wai S. Gee,[†] Glory B. Merrill,[†] and Jennifer M. Hayashi[†]

[†]Plant Mycotoxin Research, Western Regional Research Center, Agricultural Research Service, U.S. Department of Agriculture, 800 Buchanan Street, Albany, California 94710, United States

[‡]Paramount Farming Co., 33141 E. Lerdo Highway, Bakersfield, California 93308, United States

ABSTRACT: A blend of volatiles derived from the emissions of almonds at hull split and mechanically damaged almonds was compared to almond meal, the current monitoring standard for the insect pest navel orangeworm (NOW). Field trapping studies were performed to determine the blend's ability to attract adult NOW. The blend comprised racemic 1-octen-3-ol, ethyl benzoate, methyl salicylate, acetophenone, and racemic (*E*)-conophthorin. Ethyl acetate was used as a solvent with a blend component concentration of 100 mg/mL. The blend attracted both sexes of NOW when tested in five 2-week intervals spanning the first three flights of NOW in commercial almond orchards in the southern Central Valley of California. The blend demonstrated consistently higher capture rates for female NOW throughout the evaluation period, but unlike almond meal it significantly attracted males. Reported is a survey of the major and minor volatiles emitted from almonds at hull split, the key period of vulnerability to NOW infestation. Also reported is the attractancy of a formulated test blend based on the host plant volatile emissions, electroantennographic screening experiments, and field trapping studies. The results of this test blend highlight progress toward a host-plant-based attractant for NOW, a major insect pest of California tree nuts that presently lacks an adequate monitoring tool.

KEYWORDS: *almond, Amyelois transitella, field trapping, navel orangeworm, Prunus dulcis, semiochemical, volatile*

INTRODUCTION

The navel orangeworm (NOW), *Amyelois transitella* Walker (Lepidoptera: Pyralidae), is the key insect pest of tree nuts in California. Feeding by NOW larvae is responsible for damage to the kernel as well as for the introduction of mycotoxigenic fungi, both resulting in considerable economic loss to growers.[1,2] Current methods to monitor NOW populations include traps baited with virgin female NOW moths or egg traps baited with almond meal.[3] The use of virgin female NOW moths is primarily for research purposes and not practical for commercial use. The use of almond meal in egg traps is the current standard for monitoring female NOW.[4]

The female sex pheromone of NOW is known,[5,6] and recent work with the components is promising as an attractant for male NOW.[7,8] The main pheromone component (*Z*,*Z*)-11,13-hexdecadienal is unstable under orchard conditions; nevertheless, formulations in aerosol puffer delivery devices have been successfully used in mating disruption control of NOW in almond[9,10] and walnut orchards. The pheromone components in lure formulations are hindered by stability and degradation issues in the field.[4]

The identification and use of semiochemicals to attract and monitor NOW moths in almond orchards remains elusive. In 2009, Burks et al.[11] investigated use of the single nonhost compound phenyl propionate in almond and pistachio orchards to capture adult NOW. Although attractive to NOW moths, the authors concluded phenyl propionate was unlikely to be practical for economic and perceived safety reasons (personal communication, C. Burks).[11]

On the basis of field observations (B.S.H.) that female NOW are attracted to the odor of damaged almonds,[12] attention was focused on mechanically damaged almonds[13] and almonds undergoing hull split. Collection of volatiles from these sources provided the identification of both ubiquitous and distinctive volatiles of interest. Electroantennographic (EAG) analysis was used as a method to screen host plant volatiles for potential semiochemical-associated behavioral responses. Compounds eliciting the greatest chemoreception responses were formulated into various blends and screened over several growing seasons for attractancy in preliminary field trapping experiments.

The objectives of this study were (1) to perform a survey of the volatiles emitted from almonds undergoing hull split; (2) to screen the individual hull split and select damaged[13] almond volatiles via EAG and field trapping studies; and (3) to determine the attractiveness of a blend, primarily comprised of hull split volatiles, to NOW in almond orchards and compare its efficacy to the current standard monitoring lure, almond meal. The host plant volatile blend, designated as the Blend, was evaluated over five 2-week intervals spanning the first three flights of NOW in the southern Central Valley of California.

Received: June 19, 2012
Revised: July 27, 2012
Accepted: July 31, 2012
Published: July 31, 2012

dx.doi.org/10.1021/jf302658v | *J. Agric. Food Chem.* 2012, 60, 8090−8096

MATERIALS AND METHODS

Chemical Sources. Chemicals were purchased from commercial sources and used without further purification: (±)-1-octen-3-ol (98%), ethyl benzoate (99%), methyl salicylate (98%), acetophenone (99%), and ethyl acetate (99.5%) (VWR International, Wayne, PA); (±)-(*E*)-conophthorin (Contech, Victoria, BC); and, (*Z*,*Z*)-11,13-hexadecadienal (Suterra, Bend, OR).

Collection of Volatiles. An intact branch of Nonpareil or Monterey variety almonds, ca. 15 almonds, at the hull split stage were bagged with a large custom Teflon bag (40 × 25 cm) similar to the collection bag used in previous in situ studies[14] but with 0.64 cm ports for connecting Teflon tubing and utilizing a closed push/pull collection system (Figure 1) similar to the device used in 2011 by Beck et al. for ambient volatiles.[15] Briefly, a glass cartridge containing 25 g of Tenax-TA (40−60 mesh, Alltech, Deerfield, IL) was connected to a Venturi vacuum adapter using compressed air to generate the desired flow rate (35−70 mL/min). Fresh compressed air and Tenax-cleansed air were directed to the collection bag via the closed system to maintain neutral pressure inside the collection bag. Collected volatiles were chemically desorbed, concentrated, and analyzed by GC−MS as previously described.[15] Briefly, volatiles were desorbed with diethyl ether (100 mL) and concentrated to ca. 1 mL via water bath (ca. 40 °C) and Vigreux condenser, and 1 μL aliquots were injected onto J&W Scientific (Folsom, CA) DB-Wax and DB-1 (60 m × 0.32 mm i.d. × 0.25 μm) columns. The average of two separate collection periods during the 2008 growing season (July 21−August 5 and August 5−13, for Nonpareil variety, and August 12−18 and August 18−25, for Monterey variety) were each analyzed on the two different columns and reported as the percentage of minor and major volatiles in the odor profiles. All volatile identities, with the exception of β-bourbonene, were verified by comparison of retention times and fragmentation patterns to authentic standards.

Figure 1. Closed volatile collection system used to collect in situ hull split volatiles from an enclosed almond branch.

Blend Composition. Host plant blend was 1-octen-3-ol:ethyl benzoate:methyl salicylate:acetophenone:conophthorin (12:4:4:1:1 ratio), calculated for 2.5 g in 25 mL; 1-octen-3-ol (1.53 mL, 9.9 mmol), ethyl benzoate (0.48 mL, 3.3 mmol), methyl salicylate (0.43 mL, 3.3 mmol), acetophenone (0.10 mL, 0.8 mmol), and conophthorin (0.13 mL, 0.8 mmol) were diluted in ethyl acetate (22.3 mL). Rectangles (ca. 1 × 4 cm) of cotton plugs (U.S. Cotton, Gastonia, NC) were inserted into 8 mL Nalgene bottles (VWR International, Wayne, PA), 2 mL of blend (200 mg/2 mL) was added, and bottles were capped.[16] In the field, caps were replaced with emission caps having a 1.5 mm hole.

For evaluation of emission release rates, loaded and tared Nalgene bottles identical to field samples were placed in a 1-L Mason jar, capped with a lid fitted with an inlet for purified air (150 mL/min), and vented via tubing to a fume hood. The emission experiment was run in triplicate. The Mason jars containing the bottles with the Blend were then placed in an oven set at 30 °C. At approximate 24 h intervals bottles were removed, weighed, and 1.0 μL injected onto a GC-FID (Shimadzu GC-2010 Plus, Pleasanton, CA) with a J&W Scientific (Folsom, CA) DB-Wax column for quantitation. The GC−FID conditions were as follows: initial temperature, 40 °C; initial time, 0.0 min; ramp 1, 4 °C/min to 160 °C, hold 0.0 min; ramp 2, 25 °C/min to 210 °C, hold 3.0 min; inlet temperature, 200 °C, split 10:1; total flow, 22.7 mL/min; column flow, 1.79 mL/min; and linear velocity, 25.2 cm/s.

Electroantennography. The experimental and normalization procedures previously described[14] were applied to this study using the same subtraction of the female antennal response to the negative control (pentane) and the female sex pheromone component (*Z*,*Z*)-11,13-hexadecadienal. For females the crude assumption was made that female antennae should not have a full response to the female sex pheromone, and their response was therefore subtracted along with the antennal response to the negative control, pentane. Moreover, this assumption was made since at the time no compound was available as positive control for female antennal responses, unlike the sex pheromone component used for male antennal responses. Current EAG bioassays used in our laboratory compare and correct antennal responses to the host plant volatile acetophenone for both male and female NOW.[17] Male antennal responses to host plant volatiles were normalized by correcting the deflection amplitude elicited by the major component of the sex pheromone to 500 μV. Responses to volatiles were duplicated for each sex and reported as the average.

The EAG responses for the Blend concentration dose−response experiment were run using updated methods recently reported.[17] Briefly, 50 μg of the Blend in concentrations of 10 mg of the Blend in increasing dilution amounts of ethyl acetate (neat, 25, 50, 75, and 100 μL) were loaded onto assay disks, allowed to dry briefly for 30 s, and administered across the excised antennae in 2 s puffs. Reported responses were corrected by subtraction of antennal response to the negative control.

Field Trials. For the 2011 season-long evaluation of the attractiveness of the host plant blend, a randomized complete block design with five replicates per treatment was configured in five almond orchards (64−256 ha) located in Kern County, CA. Traps used were standard orange plastic delta traps with glue liners (Suterra, Bend, OR). The treatments were traps baited with (1) Nalgene bottles containing 200 mg of the Blend solution, (2) bottles with only cotton serving as a negative control, (3) traps baited with almond meal (ca. 18.6 g) in standard egg traps (Trécé, Adair, OK) as a female attractant, and (4) wire mesh cages containing three virgin females as a male attractant (30 m downwind of other treatments). Trap catches were collected weekly, NOW adult moths were counted and sexed, females were dissected to determine their mating status, and fresh blend bottles were placed in the traps. Each moth capture experiment comprised two 1-week trapping intervals in 2011: April, April 30−May 5; May, May 13−27; June, June 17−July 1; July, July 2−17; and, August, August 5−19. Data from periods of no NOW pressure—blend and almond meal treatments having no captures and no or significantly low male capture in virgin female baited traps—were not included in the analysis. Trap data were analyzed with one-way, repeated measures ANOVA and followed by pairwise multiple comparisons with the Fisher LSD method.

Preliminary field trapping screening of attractiveness of individual volatiles and simple component blends were performed in Kern County, CA, over the 2008−2010 growing seasons. For testing of individual components, rubber white septa (Sigma-Aldrich, St. Louis, MO) impregnated with pentane solutions containing 5 mg of each test component were hung in orange delta traps. Moth captures of individual components were compared to traps baited with almond meal. For simple blends septa with 5 mg of total components were

placed in delta traps, hung in five replicate blocks, and again compared to traps baited with almond meal.

RESULTS

Twenty-one compounds were observed and identified in minor to major amounts from Nonpareil and Monterey varieties of almonds during the hull split period (Table 1). Emissions between the cultivars were relatively similar in composition, with generally minor differences in relative amounts. Some notable differences between the two cultivars were a greater proportion of monoterpenes and the sesquiterpenes β-caryophyllene and α-humulene in the Nonpareil odor profile. The amounts of benzaldehyde and conophthorin were greater in the Monterey odor profile. Twelve of the 21 volatiles in Table 1 were also detected from damaged almonds[13] and are indicated with a superscript. The compound 1-octen-3-ol, not detected in the hull split experiment but detected from damaged almond emissions, elicited a relatively large female antennal response.

Table 1. Major (≥10%) and Minor (< 10% and >1%) Volatiles Collected in Situ from Hull Split Nonpareil (NP) and Monterey (MO) Almonds, Kern County, CA, 2008

		average %		EAG response (μV)[a]	
identity	source[b]	NP	MO	♂	♀
α-pinene[c]	Alph	3.31	0.87	0	0
camphene[c]	Iso	1.84	1.50	0	10
β-pinene[c]	Iso	3.49	0.00	0	0
myrcene[c]	Iso	1.58	0.48	25	0
limonene[c]	Alph	15.00	6.78	0	0
(*E*)-β-ocimene	Iso	2.13	1.33	183	240
acetoin[c]	Ald	1.55	3.05	0	95
conophthorin[c]	Con	1.84	7.98	55	130
(*E*)-4,8-dimethyl- 1,3,7-nonatriene[c]	Iso	1.90	1.65	0	0
(*Z*)-hex-3-enyl acetate	Bed	2.06	3.91	0	0
benzaldehyde[c]	Ald	22.46	49.95	0	0
β-bourbonene[cd]	Tent	3.27	0.00	–	–
β-caryophyllene	Iso	20.35	2.72	0	190
methyl benzoate	Ald	1.48	2.91	10	5
acetophenone	Alph	2.23	4.02	0	260
ethyl benzoate[c]	Alph	0.00	1.69	0	525
α-humulene	Ald	7.89	1.64	187	250
(*E*,*E*)-α-farnesene	Iso	4.79	3.07	160	155
methyl salicylate	Alph	0.01	0.76	245	175
2-phenylethanol[c]	Ald	1.61	3.95	54	320
phenol	Ald	0.62	1.02	0	0
1-octen-3-ol[e]	Alph	–	–	0	475

[a]Corrected to (*Z*,*Z*)-13,16-hexadecadienal and pentane. [b]Source of compound for authentication and EAG studies: Ald, Sigma Aldrich; Alph, Alpha Aesar; Bed, Bedoukian; Con, Contech; Iso, previously isolated by a researcher in this laboratory (Buttery, Flath, or Binder); Tent, tentative assignment. [c]Compounds also seen in mechanically damaged almond study ref 13. [d]Compound not available for EAG or authentication. [e]From damaged almond study.

Evaluation of the EAG data in Table 1 for elicitation of responses from primarily females provided the main basis for the almond-odor-derived blend reported; of these methyl salicylate and (±)-conophthorin, ranked 8th and 10th most stimulating, were the only components included in the final blend that elicited female antennal responses of less than 200 μV. A more complex, eight-component volatile blend that included α-humulene, 2-phenylethanol, and nonanal was field tested and provided no improvement in attraction. The more complex blend was statistically equivalent yet numerically lower in responses than the five-component blend reported here (1.25 ± 0.29 vs 1.50 ± 0.24, overall NOW captured, respectively), thus demonstrating that a simpler blend was similarly effective in trapping NOW. The compound nonanal was detected in the damaged almond study;[13] however, in the hull split volatile collection experiment nonanal was only detected on one GC−MS column and was thus listed as a transient and not included in Table 1.

Traps baited with almond meal captured 19 female and 1 male NOW over the entire seasonal test period, with capture rates in the April interval significantly greater than blank traps, which caught a total of 1 female and 1 male NOW (Table 2).

For captures of both male and female NOW combined (row labeled NOW in Table 2), the Blend significantly exceeded almond meal captures in all test intervals. For female moth captures, the Blend significantly exceeded almond meal captures in the April (early first flight) and June (early to mid second flight). The Blend attracted a large percentage of mated females (93%) versus virgin females with the only virgin females captured during the April trapping interval. For male moth captures the Blend significantly exceeded almond meal captures in April, June, July, and August intervals.

Male, female, and combined-gender captures for the Blend statistically exceeded almond meal for the overall test period, which averaged the pooled April through August intervals (overall block in Table 2). Male captures significantly exceeded female captures for the Blend during the April interval and the overall averages, while female captures significantly exceeded male captures for almond meal during the April interval and the overall averages.

Blend emission release rates over the 1-week evaluation period provided the following data (average emission rates in mg/h, average blend composition ratio based on emission rates, and comparison to original composition blend ratio as determined by GC−FID): ethyl acetate (8.23, 74.0, 100.4), conophthorin (0.11, 1.0, 1.0), 1-octen-3-ol (1.46, 13.1, 12.5), acetophenone (0.12, 1.1, 1.0), ethyl benzoate (0.50, 4.5, 4.3), and methyl salicylate (0.40, 3.6, 3.4). Graphs of emission rates as a function of time are provided in Figure 2. The linear regression trendline for each component is provided in the graphs in Figure 2. However, when an exponential regression analysis was performed for each component the r^2 values were nearly identical, albeit slightly numerically lower (excluding ethyl acetate) than the linear trendline. Graphing of the average vial weights over time during the gravimetric analysis gave an r^2 = 0.9998 when a linear trendline was applied.

Four-point calibration curves for each component gave the following r^2 values at the specified concentration range: 1-octen-3-ol, 0.9964, 3.13−50.00 mM; ethyl benzoate, 0.9978, 1.56−12.50 mM; methyl salicylate, 0.9917, 1.56−12.50 mM; acetophenone, 0.9988, 0.39−3.13 mM; and, conophthorin, 0.9967, 0.39−3.13 mM.

The dose−response experiment analyzing female NOW antennal response via EAG as a function of concentration of the Blend in ethyl acetate (10 mg/*x* μL of solvent) gave the data presented as a graph in Figure 3. The neat blend (no solvent) was statistically greater than the blends at high dilution rates with ethyl acetate as solvent. The four concentrations (100, 75,

Table 2. Mean Captures of Male and Mated Female NOW per Trap per Week, Kern County, CA, 2011

test interval[b]	Flt	N	moths	Treatment[a] host plant blend[c]	Treatment[a] almond meal	Treatment[a] blank	One-way ANOVA	males in virgin female-baited traps (range)
April[d]	1	10	NOW	11.30 ± 1.97 a	1.60 ± 0.34 b	0.10 ± 0.10 c	$F = 27.87$; df: 2, 27; $P < 0.001$	
			female	4.40 ± 0.97 a[f]	1.60 ± 0.34 b[f]	0 c	$F = 13.64$; df: 2, 27; $P < 0.001$	
			male	6.90 ± 1.10 a[f]	0 b[f]	0.10 ± 0.10 b	$F = 38.86$; df: 2, 27; $P < 0.001$	86.57 ± 18.74 (27−183)
May	1	5	NOW	1.60 ± 0.60 a	0.20 ± 0.20 b	0 b	$F = 6.91$; df: 2, 12; $P = 0.018$	
			female	0.60 ± 0.25	0.20 ± 0.20	0	$F = 3.50$; df: 2, 12; $P = 0.081$	
			male	1.00 ± 0.63	0	0	$F = 2.50$; df: 2, 12; $P = 0.143$	20.60 ± 13.34 (0−105)
June	2	7	NOW	1.14 ± 0.26 a	0 b	0 b	$F = 19.20$; df: 2, 18; $P < 0.001$	
			female	0.43 ± 0.20 a	0 b	0 b	$F = 4.50$; df: 2, 18; $P = 0.035$	
			male	0.76 ± 0.29 a	0 b	0 b	$F = 6.25$; df: 2, 18; $P = 0.014$	26.80 ± 10.00 (0−102)
July	2	9	NOW	2.00 ± 0.58 a	0.22 ± 0.22 b	0.11 ± 0.11 b	$F = 11.74$; df: 2, 24; $P < 0.001$	
			female	0.44 ± 0.24	0.11 ± 0.11	0.11 ± 0.11	$F = 1.14$; df: 2, 24; $P = 0.344$	
			male	1.56 ± 0.63 a	0.11 ± 0.11 b	0 b	$F = 6.34$; df: 2, 24; $P = 0.009$	17.80 ± 6.54 (0−52)
August	3	7	NOW	1.14 ± 0.40 a	0.14 ± 0.14 b	0 b	$F = 6.22$; df: 2, 18; $P = 0.014$	
			female	0.71 ± 0.42	0.14 ± 0.14	0	$F = 2.25$; df: 2, 18; $P = 0.148$	
			male	0.43 ± 0.20 a	0 b	0 b	$F = 4.50$; df: 2, 18; $P = 0.035$	30.00 ± 10.28 (2−85)
overall		38	NOW	4.08 ± 0.89 a	0.53 ± 0.15 b	0.05 ± 0.04 b	$F = 20.19$; df: 2, 111; $P < 0.001$	
			female	1.55 ± 0.39 a[f]	0.50 ± 0.15 b[f]	0.03 ± 0.03 b	$F = 12.72$; df: 2, 111; $P < 0.001$	
			male	2.53 ± 0.54 a[f]	0.03 ± 0.03 b[f]	0.03 ± 0.03 b	$F = 21.46$; df: 2, 111; $P < 0.001$	
total[e]			NOW	155	20	2		
			female	59	19	1		
			male	96	1	1		

[a]Capture values are means ± SE. Data in rows followed by different letters are significantly different ($P < 0.05$), by one-way, repeated measures ANOVA followed by all pairwise multiple comparisons by Fisher LSD method. [b]April, 4/30−5/5 May, 5/13−5/27; June, 6/17−7/1; July, 7/2−7/17; August, 8/5−8/19. [c]Females captured in May−August traps baited with the Blend were all mated and with one spermatophore. [d]Five-day period. [e]Total, combined captures over all test periods. [f]Significant difference between male and female captures, by paired t test, $P < 0.005$.

50, and 25 μL ethyl acetate) were statistically equivalent. The field rate corresponds to 10 mg of blend components in 100 μL of ethyl acetate.

DISCUSSION

The volatile survey of Nonpareil and Monterey almond cultivars at hull split provided a relatively similar composition with a total of 21 compounds, of which 18 were shared between the two cultivars. A number of the trace and transient peaks not included in Table 1 have been identified in other almond host plant volatile studies and have been analyzed via EAG for potential activity.[14] For instance, the compound nonanal was detected in the 2009 in situ study by Beck and co-workers[14] and was later reported by Leal and co-workers to bind with NOW olfactory proteins.[18] The volatiles identified in Table 1 were intended as a survey and as a starting point for the testing of compounds and blends for attracting NOW. The emissions between the two cultivars had relatively minor differences in reported amounts except for benzaldehyde, β-caryophyllene, α-humulene, and conophthorin. This disparity in relative amounts may be explained by the cultivar hull differences; a more thorough comparison study of the hull volatile emissions would be necessary to provide a more definitive volatile output difference between the two cultivars.

To begin the EAG investigation of hull split volatiles, an initial blend that represented the overall bouquet of volatiles was formulated and comprised the relatively high-EAG value components. These included (*E*)-β-ocimene, (±)-conophthorin, acetophenone, ethyl benzoate, α-humulene, (*E*,*E*)-α-farnesene (impure), methyl salicylate, and 2-phenylethanol in the ratio of 3:10:6:2:10:8:1:3. The ratio was based on the average GC−MS responses of Nonpareil and Monterey emissions noted in Table 1. However, during early EAG and field-trapping studies, many of the other components were eliminated, and 1-octen-3-ol, a volatile from damaged almonds[13] eliciting a high EAG response, was eventually inserted to provide the basic framework of successful blend components. During the blend component screening process, over 50 field-trapping iterations using the components from this initial mixture were performed and a basic blend comprising 1-octen-3-ol:ethyl benzoate:methyl salicylate in a 3:1:1 ratio was identified as being the minimum basic components necessary for adult moth attraction. However, the number of moths captured with this basic blend never exceeded the number of moths caught in the almond meal during the limited screening studies. During these trials, the addition of acetophenone into the blend helped to increase the number of observed NOW captures. Subsequent addition of (±)- conophthorin into the blend of (±)-1-octen-3-ol, ethyl benzoate, methyl salicylate, and acetophenone provided higher and more consistent capture numbers during these field trapping studies. This was an interesting result, since (±)-conophthorin by itself performed relatively poorly in our limited field trial studies, as did all other volatiles when tested individually. However, the unique structure of conophthorin and its appearance in damaged[13] and hull split almonds prompted further field evaluation when combined with other candidate host plant volatiles. Conversely, the compound (*E*)-β-ocimene demonstrated a good antennal response (ranked third for males and sixth for females) but did not perform well

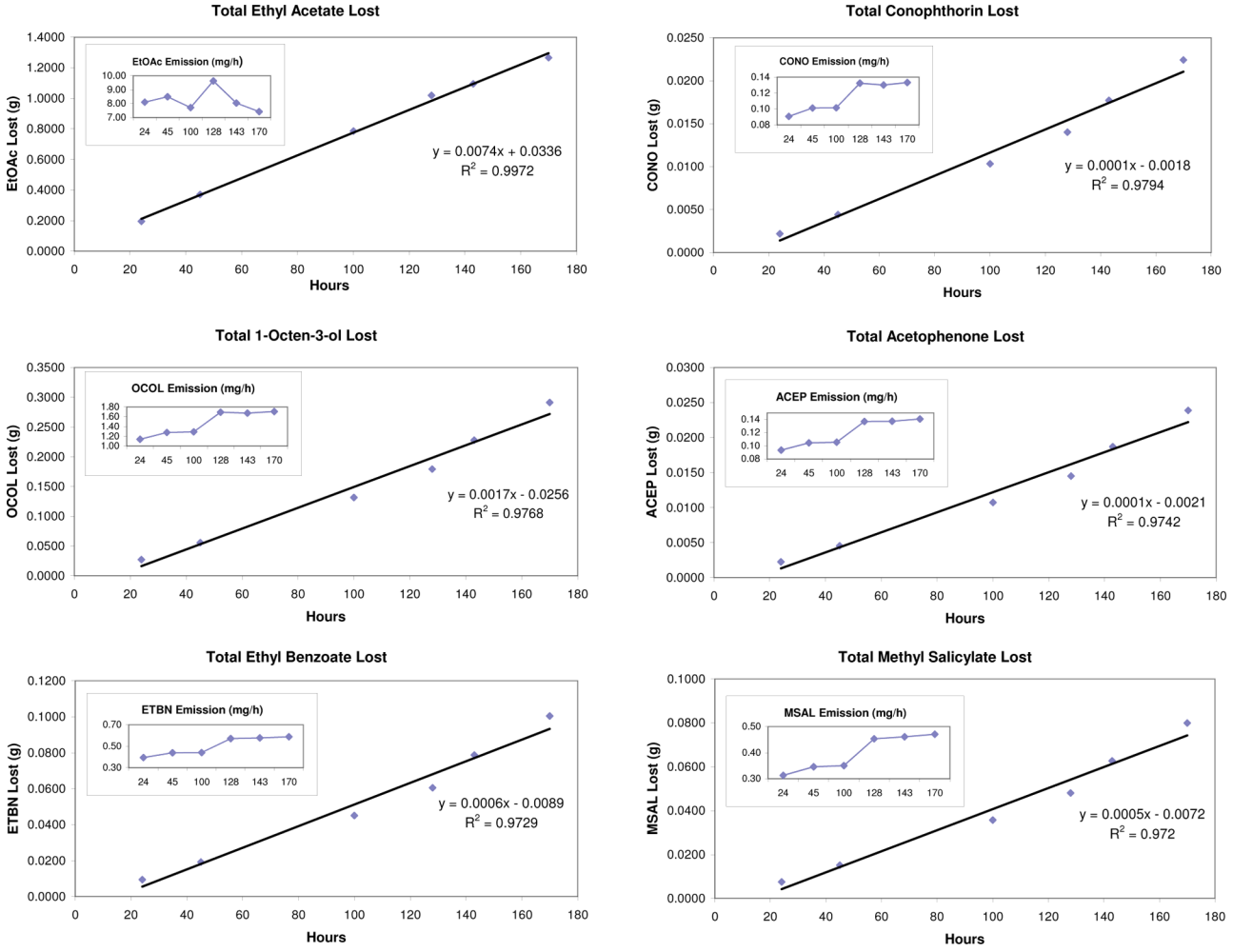

Figure 2. Emission release rates for each Blend component and solvent at 30 °C with amount lost (g of material) versus time. Insets show concentration of emitted component (mg/h) versus time. Shown are linear regression analyses for modeling emission release rates.

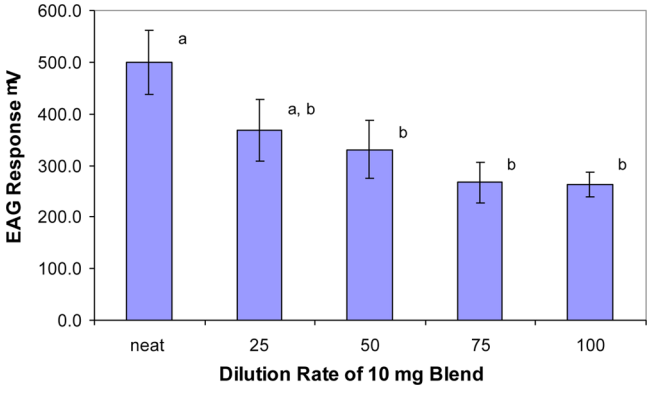

Figure 3. Female NOW EAG response to concentrations of 10 mg of Blend mixed with varying dilution rate amounts of ethyl acetate. EAG conditions were 50 μg total of mixtures and $N = 7$ for each concentration. Responses with different letters are significantly different ($P < 0.05$), by one-way ANOVA followed by pairwise comparison by Student's t test.

when evaluated either alone or in various simple blends during the screening field trapping studies. Concurrent EAG studies of all of the iterations were not performed, and thus, no correlations between EAG and capture results can be made at this time.

The components of the Blend are common plant volatiles with demonstrated semiochemical-elicited behavior in insects.[19] 1-Octen-3-ol is a ubiquitous volatile from both fungal and plant hosts,[13] as well as a breakdown product of linoleic acid.[20] The unassigned stereoisomer has been classified as an attractant for numerous insects.[19] The *R*- and *S*-enantiomers of 1-octen-3-ol were evaluated during the field trapping screening studies, but their inclusion in blends did not demonstrate differential chiral capture activity greater than similar blends using the less expensive racemic 1-octen-3-ol. The spiroacetal conophthorin, most commonly known as a semiochemical for bark beetles,[21,22] has origins from plants and insects[23] but was detected from mechanically damaged almonds.[13]

Interestingly, the attraction of males to the Blend has positive implications for its potential use, or an optimized version, for monitoring NOW populations in orchards undergoing mating disruption treatments, wherein males are not readily captured in pheromone-baited monitoring traps in orchard environments inundated with synthetic pheromone.

The initial assumption that the formulated Blend would only attract female NOW was incorrect, and in fact, the results in Table 2 demonstrate that the Blend attracted more male adult moths than female adult moths. One possible explanation for this result may be explained by a report[24] that observed male *Heliconius* butterflies displaying mate-searching behavior around

dx.doi.org/10.1021/jf302658v | J. Agric. Food Chem. 2012, 60, 8090−8096

the host plant. In their report they suggest that the host plant volatiles may be alerting the males to a location to find potential partners.

Another interesting result from the current study was the mating status of the captured females. The traps in the test intervals May through August captured only mated females (with one spermatophore each) and in the April trap test interval three of the 44 females captured were virgins. However, it is not unusual to capture the occasional unmated female NOW in oviposition attractant traps (personal observation, B.S.H.). On the basis of the initial assumption that the primary behavior of gravid females is searching for an optimal ovipositional site, it makes sense for the mated females to be attracted to these particular host plant volatiles.[25]

Ethyl acetate was used as a solvent to help stabilize the Blend components. Traps baited with ethyl acetate were not attractive to NOW moths in preliminary 2010 experiments. Initial field trapping screening indicated ethyl acetate did not have an adverse effect on the Blends' ability to attract NOW moths, which concurs with a study of the strawberry sap beetle that included ethyl acetate as a blend component in high ratio.[26] Conversely, ethyl acetate as a host plant volatile has been shown to induce pheromone production from the African palm weevil and is a necessary component during field attractancy studies.[27] Hypothetically, the possible hydrolysis of ethyl acetate would generate acetic acid, which has been shown to increase codling moth captures when combined with other plant volatiles.[28] This possibility and in depth emission rates of the blend components in ethyl acetate will be considered in future studies. It should be noted that ethyl acetate in addition to ethanol and acetic acid have been detected in other in vitro almond emission studies, and all three compounds are ubiquitous volatiles emitted in large amounts from most ripe or ripening fruits. The use of ethanol vs ethyl acetate as a solvent for the Blend was compared concurrently in field trapping studies. The lower number of observed moths captured in the Blend with ethanol as the solvent prompted the choice of ethyl acetate; however, this comparison was for internal purposes only and should not be considered definitive.

Overall, the demonstrated attractancy of the Blend shows promise for the development of a host-plant-based attractant; however, there are several aspects of the Blend formulation that require further optimization, with the method of release an obvious first step. Initially, septa charged with the host plant volatiles were used during the screening process, but it was decided to switch to the vials with cotton and a hole in the cap for the season-long trapping study to ensure a relatively high and consistent release rate. Additionally, the use of a solvent appeared to have stabilized the emission of the ratio of the host plant volatiles and lengthened the duration of emission. An isothermal (30 °C) study of the evaporative emissions of the Blend components in ethyl acetate indicated a steady emission at the desired ratios for more than 7 days with the relative percentage of ethyl acetate dropping from ca. 80% to 70% over the evaluation period (Figure 2). It should be noted that the total amount of each component lost over time (Figure 2) appears to be linear; however, when both the linear and exponential trendline is applied the r^2 values are essentially equivalent. This similarity of trendline fits among regression analyses has been observed[29] with other kairomone release rates in other systems, and thus, no conclusions are drawn at this juncture. If the use of solvent as a host plant emission mediator is continued, then a study that varies both the concentration and solvent type may be beneficial. Some preliminary studies using ethanol in place of ethyl acetate indicated that ethyl acetate was more effective in terms of comparative trap numbers when used as a cosolvent; however, these two solvents may play varying roles at different concentrations and different cap hole sizes.

To address any ambiguity regarding the role of ethyl acetate as a solvent, the use of the Blend in a membrane dispenser will be explored in subsequent studies. An EAG dose−response experiment that measured the female antennal response to varying concentrations of the Blend in ethyl acetate was conducted (Figure 3) and the EAG responses indicated that the Blend without the solvent would be more effective than the 100 mg/mL concentration that was used in this study. However, the initial field trapping studies that compared neat Blend to the Blend in ethyl acetate showed slight adult moth preference for the Blend in ethyl acetate.

The host-plant-based Blend from almonds was more attractive to adult NOW than the standard almond meal bait. The higher capture numbers and increased consistency present an opportunity for an improved host-plant-based monitoring approach for NOW in orchards managed either conventionally or by mating disruption. While these results do not infer commercial use, they do highlight an important incremental step in host-plant-based volatile blends for monitoring NOW, which has proven elusive. A comprehensive, high-replicate electroantennographic screening of all available almond emission volatiles is currently underway and will assist in further optimization of host plant volatiles as a potential monitoring tool.

AUTHOR INFORMATION

Corresponding Author

*Telephone (510) 559-6154. Fax (510) 559-6493. E-mail john.beck@ars.usda.gov.

Funding

Research was conducted under USDA-ARS CRIS Project 5325−42000−037−00D, CRADA 58−3K95−7−1198 with Paramount Farming Company, and TFCA 58−5325−8−419 with the Almond Board of California.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors thank Johnny Magana and Ashlee Pedro (PFC), and James Baker (USDA-ARS) for their valuable contributions. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

REFERENCES

(1) Campbell, B. C.; Molyneux, R. J.; Schatzki, T. F. Current research on reducing pre- and post-harvest aflatoxin contamination of U.S. almonds, pistachio, and walnut. *J. Toxicol. Toxin Rev.* **2003**, *22*, 225−266.

(2) Palumbo, J. D.; Mahoney, N. E.; Light, D. M. Navel orangeworm (*Amyelois transitella*) as a vector of *Aspergillus flavus* on almonds. *Phytopathology* **2008**, *98*, S119.

(3) Burks, C. S.; Higbee, B. S.; Siegel, J. P.; Brandl, D. G. Comparison of trapping for eggs, females, and males of the navel orangeworm (Lepidoptera: Pyralidae) in almonds. *Environ. Entomol.* **2011**, *40*, 706−713.

(4) Higbee, B. S.; Burks, C. S. Effect of bait formulation and number of traps on detection of navel orangeworm (Lepidoptera: Pyralidae) oviposition using egg traps. *J. Econ. Entomol.* **2011**, *104*, 211−219.
(5) Coffelt, J. A.; Vick, K. W.; Sonnet, P. E.; Doolittle, R. E. Isolation, identification, and synthesis of a female sex pheromone of the navel orangeworm, *Amyelois transitella* (Lepidoptera: Pyralidae). *J. Chem. Ecol.* **1979**, *5*, 955−966.
(6) Leal, W. S.; Parra-Pedrazzoli, A. L.; Kaissling, K.-E.; Morgan, T. I.; Zalom, F. G.; Pesak, D. J.; Dundulis, E. A.; Burks, C. S.; Higbee, B. S. Unusual pheromone chemistry in the navel orangeworm: Novel sex attractants and a behavioral antagonist. *Naturwissenschaften* **2005**, *92*, 139−146.
(7) Kanno, H.; Kuenen, L. P. S.; Klingler, K. A.; Millar, J. G.; Cardé, R. T. Attractiveness of a four-component pheromone blend to male navel orangeworm moths. *J. Chem. Ecol.* **2010**, *36*, 584−591.
(8) Kuenen, L. P. S.; McElfresh, J. S.; Millar, J. G. Identification of critical secondary components of the sex pheromone of the navel orangeworm (Lepidoptera: Pyralidae). *J. Econ. Entomol.* **2010**, *103*, 314−330.
(9) Higbee, B. S.; Burks, C. S. Effects of mating disruption treatments on navel orangeworm (Lepidoptera: Pyralidae) sexual communication and damage in almonds and pistachios. *J. Econ. Entomol.* **2008**, *101*, 1633−1642.
(10) Shorey, H. H.; Gerber, R. G. Use of puffers for disruption of sex pheromone communication among navel orangeworm moths (Lepidoptera: Pyralidae) in almonds, pistachios, and walnuts. *Environ. Entomol.* **1996**, *25*, 1154−1157.
(11) Burks, C. S.; Higbee, B. S.; Kuenen, L. P. S.; Brandl, D. G. Monitoring *Amyelois transitella* males and females with phenyl propionate traps in almonds and pistachios. *Entomol. Exp. Appl.* **2009**, *133*, 283−291.
(12) Roitman, J. N.; Merrill, G. B.; Higbee, B. S. What attracts navel orangeworm to oviposit preferentially on wounded almonds rather than unblemished fruit? The search for a volatile attractant. Proceedings of the 4th Fungal Genomics, 5th Fumonisin Elimination, and 17th Aflatoxin Elimination Workshop. Oct. 25−28, 2004; p 27.
(13) Beck, J. J.; Higbee, B. S.; Merrill, G. B.; Roitman, J. N. Comparison of volatile emissions from undamaged and mechanically damaged almonds. *J. Sci. Food Agric.* **2008**, *88*, 1363−1368.
(14) Beck, J. J.; Merrill, G. B.; Higbee, B. S.; Light, D. M.; Gee, W. S. In situ seasonal study of the volatile production of almonds (*Prunus dulcis*) var. 'Nonpareil' and relationship to navel orangeworm. *J. Agric. Food Chem.* **2009**, *57*, 3749−3753.
(15) Beck, J. J.; Higbee, B. S.; Gee, W. S.; Dragull, K. Ambient orchard volatiles from California almonds. *Phytochem. Lett.* **2011**, *4*, 199−202.
(16) Landolt, P. J.; Alfaro, J. F. Trapping *Lacanobia subjuncta*, *Xestia c-nigrum,* and *Mamestra configurata* (Lepidoptera: Noctuidae) with acetic acid and 3-methyl-1-butanol in controlled release dispensers. *Environ. Entomol.* **2001**, *30*, 656−662.
(17) Beck, J. J.; Light, D. M.; Gee, W. S. Electroantennographic bioassay as a screening tool for host plant volatiles. *J. Vis. Exp.* **2012**, *63*, e3931.
(18) Liu, Z.; Vidal, D. M.; Syed, Z.; Ishida, Y.; Leal, W. S. Pheromone binding to general odorant-binding proteins from the navel orangeworm. *J. Chem. Ecol.* **2010**, *36*, 787−794.
(19) El-Sayed, A. M. The pherobase: Database of insect pheromones and semiochemicals. URL http://www.pherobase.com/ Accessed April 21, 2012.
(20) Hoffmann, G. 1-Octen-3-ol and its relation to other oxidative cleavage products from esters of linoleic acid. *J. Am. Oil Chem. Soc.* **1962**, *39*, 439−444.
(21) Allison, J. D.; Borden, J. H.; Seybold, S. J. A review of the chemical ecology of the Cerambycidae (Coleoptera). *Chemoecology* **2004**, *14*, 123−150.
(22) Francke, W. Spiroacetals in insects. *Curr. Org. Chem.* **2001**, *5*, 233−251.
(23) Zhang, Q.-H.; Tolasch, T.; Schlyter, F.; Francke, W. Enantiospecific antennal response of bark beetles to spiroacetal (*E*)-conophthorin. *J. Chem. Ecol.* **2002**, *28*, 1839−1852.
(24) Estrada, C.; Gilbert, L. E. Host plants and immatures as mate-searching cues in *Heliconius* butterflies. *Anim. Behav.* **2010**, *80*, 231−239.
(25) Renwick, J. A. A.; Chew, F. S. Oviposition behavior in Lepidoptera. *Annu. Rev. Entomol.* **1994**, *39*, 377−400.
(26) Cha, D. H.; Loeb, G. M.; Linn, C. E.; Roelofs, W. L. Electrophysiological and behavioral identification of a volatile blend involved in host location of female strawberry sap beetle *Stelidota geminate*. *Entomol. Exp. Appl.* **2011**, *140*, 153−162.
(27) Reddy, G. V. P.; Guerrero, A. Interactions of insect pheromones and plant semiochemicals. *Trends Plant Sci.* **2004**, *9*, 1360−1385.
(28) Knight, A. L.; Light, D. M.; Trimble, R. M. Identifying (*E*)-4,9-dimethyl-1,3,7-nonatriene plus acetic acid as a new lure for male and female codling moth (Lepidoptera: Tortricidae). *Environ. Entomol.* **2011**, *40*, 420−430.
(29) Light, D. M.; Beck, J. J. Characterization of microencapsulated pear ester (2*E*,4*Z*)-ethyl-2,4-decadienoate, a kairomonal spray adjuvant against neonate codling moth larvae. *J. Agric. Food Chem.* **2010**, *58*, 7838−7845.